WHITE DWARF STARS AT ULTRAVIOLET WAVELENGTHS

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ABSTRACT

Numerous discoveries with the IUE Observatory have stimulated research on most spectroscopic types of degenerate dwarf stars. The hottest helium-rich cases apparently have substantial abundances of certain ions heavier than helium, due most likely to selective radiative acceleration. Hydrogen DA stars show trace abundances at temperatures as low as 20,000 K and provide evidence for modest outflowing winds. Cooler DA stars exhibit mysterious broad features near 1400Å and 1600Å. The element carbon is almost omnipresent in cool helium-rich stars, unless metallic features are seen instead. The carbon is most likely dredged-up by a deep convective envelope. The metals are attributed to interstellar accretion. IUE has played an important role in temperature determinations for helium-rich and magnetic stars. White dwarf components in detached and cataclysmic binaries have been studied extensively with IUE, often for the first time. Among the potential results are mass determinations and information on the photospheric temperature distributions for accreting primaries.

INTRODUCTION

White dwarfs normally show quite dull optical spectra; even with a 4-5 meter telescope and state-of-the-art detectors, only the dominant atmospheric constituent appears. Hydrogen atmosphere cases are classified DA, regardless of temperature; stars showing neutral helium lines are called DB. Stars too cool for the dominant element to be excited generally show no optical features, and are classified DC. The reason for these monoelemental atmospheres is that -- at the high surface gravities -- the lightest element in the envelope floats to the top rather quickly, while heavier elements sink. After all, the physical depth of a white dwarf atmosphere is of order a hundred meters!

Of course, if the foregoing were completely true, I wouldn't have had a Ph.D. thesis derived from detailed optical spectrophotometry (Liebert 1977). There have been three kinds of (nonmagnetic) exceptional white dwarf spectra, all associated with helium-rich atmospheres: (1) Some DB stars show traces of hydrogen, near the limit of detectability; (2) metallic line (DZ) stars show a few metals, but generally no hydrogen or carbon; and (3) the carbon-band white dwarfs generally show no metals or hydrogen. At the time of launch of IUE, nobody understood how these three groups related to each other, or why they were exceptional.

After six years of IUE observations, the vast majority of targetted degenerate stars have revealed ultraviolet spectral features. Generally, only

those white dwarfs too cool and faint for this 0.45-meter telescope retain a strict DC (featureless) spectral type. In the following discussion, several areas of white dwarf research which have been advanced by IUE observations are briefly reviewed. These discoveries are the dominant reason that my earlier review (Liebert 1980) is now out of date.

TRACE ELEMENTS IN HOT WHITE DWARFS

It is logical that the very hottest objects would be among the best candidates for showing multi-element atmospheres. Recently-formed degenerate stars are, of course, less likely to have undergone gravitational diffusion. Moreover, selective radiative acceleration of certain ions having resonance transitions near the star's Planckian radiation peak may result in the suspension or even expulsion of these ions. For unsaturated line transitions, the radiative acceleration depends on T_{eff}^4/A (where A is the atomic mass of the element being considered). Stars with helium-rich atmospheres seemed to be more logical candidates than hydrogen-rich cases for two reasons. First, helium-rich atmospheres generally have higher pressures at a given optical depth, and the resulting increased line widths reduce the effect of saturation on the lines. Secondly, the reduced continuum opacities mean that trace elements are detectable at lower column densities.

Indeed, the very hot pulsating PG1159-035 stars show carbon and probably nitrogen features at optical wavelengths (McGraw et al. 1979; Liebert and Green 1979); a rich variety of ultraviolet metallic features are revealed with the low resolution IUE camera (Wesemael, Green and Liebert 1984). Still, there is a possible discrepancy in temperature estimates for these helium-rich stars. IUE spectra appear to show weak C III, N III transitions, which suggests that $T_{eff} \lesssim 10^5$ K. This is a bit lower than the estimate for the prototype based on the Einstein X-ray detection and the very hot far-UV energy distribution measured with the Voyager detector (Wegner et al. 1982). The supposedly cooler DO star PG1034+001 shows strong N V but no N III features in a high dispersion spectrum (Sion, Liebert and Wesemael 1984). A well-exposed ultraviolet echelle spectrum of PG1159-035 might clear up the problem, showing whether the low ionization features -- if real -- belong to the photosphere. The first heavy element abundance determinations for a helium-rich object -- PG1034+001 -- indicate substantial nitrogen and carbon values -- log (N/He) ~ -2.5 and log (C/He) ~ -2.5 (Sion, Liebert and Wesemael 1984).

For reasons stated earlier, it was more surprising that apparently-photosphere metal features have now been found in some hot DA (hydrogen) white dwarfs, ranging in temperature from about 70,000 K (Feige 24, Dupree and Raymond 1982) to 22,000 K (W1346, Bruhweiler and Kondo 1983). To be sure these transitions of silicon, nitrogen and carbon are quite weak (a few hundred milliangstroms or less) and detectable only with the IUE echelle. Some show radial velocities in agreement with optical H values, though an origin outside the photosphere cannot be ruled out. Others show "shortward shifted" velocities, leading Bruhweiler and Kondo (1983) to argue that there is evidence for modest outflowing winds in DA stars down to T_{eff} ~ 20,000 K. The lack of such features in stars as cool as 40 Eri B (~ 16,000 K) indicates that the radiative acceleration and/or wind processes are no longer operative

at lower temperatures. The first photospheric metal-line calculations for Feige 24 and W1346 indicate abundances of N, C and Si some 1-3 orders of magnitude below solar and with very non-solar relative values (Wesemael, Henry and Shipman 1984). The radiation fields of hot white dwarfs are capable of producing circumstellar Stromgren spheres; their number densities suggest the possibility that they are substantial contributors to the ionization balance of the interstellar medium (Dupree and Raymond 1983).

TRACE ELEMENTS IN COOL WHITE DWARFS

It was not surprising that the cool, helium-rich degenerate stars showing metallic lines at optical wavelengths unveiled a harvest of new lines at IUE wavelengths. Such studies of key stars as by Shipman and Greenstein (1983) and Cottrell and Greenstein (1980) have shown that a simple theory of accretion from an interstellar cloud followed by diffusion does not work. It is still necessary to explain why hydrogen is so effectively screened out (Liebert 1979), and why the heavier metals (Ca, Mg, Fe) are accreted more readily than the CNO species. The recent papers by Alcock and Illarionov (1980) and Truran and Wesemael (1982) lend insight into how a more complicated accretion theory might be made to work -- see also Shipman (1984).

On the other hand, IUE observations have now linked together the cool DC degenerates with those showing molecular carbon (C_2) at optical wavelengths: Both groups exhibit atomic and molecular carbon features at ultraviolet wavelengths. Comprehensive studies summarized by Koester, Weidemann and Zeidler -K.T. (1982), and Wegner and Yackovich (1984) indicate that the features span the range 6,000 - 12,000 K. Koester et al. argued that the trace carbon abundance is due to contamination of the outer helium convection zone by the tail of the equilibrium carbon distribution. Models predicting the amounts of dredged-up carbon by Fontaine et al. (1984) are in rather good agreement with abundance determinations which peak in the stars near 10 - 12,000 K. The abundances are generally low enough that the carbon features may be masked in those stars which accrete from the ISM: The metals supply extra electron donors, which increase the continuum opacity, and hide the carbon.

Despite the absence of sharp metallic or carbon features, it is perhaps the cool DA stars which exhibit the biggest surprises at IUE wavelengths. A fair number of stars show strong, broad or asymmetric absorption dips centered near 1400Å and 1600Å, starting with the discovery of the former in excellent 40 Eri B spectra by Greenstein (1980). Both features appear strongest at temperatures near 10,000 K but have been detected in stars as high as 20,000 K. Tentative explanations include molecular hydrogen transitions (Greenstein 1980), Si II autoionization lines (Sion, Wesemael and Guinan 1984) and bound-free edges of Ca II and Mg II (Wegner 1984a,b). It is possible that the 1600Å feature is related to some seen in Lambda Bootis and other peculiar A stars of lower gravity.

TEMPERATURES AND OTHER STELLAR PARAMETERS

The IUE telescope has proven moderately useful as an ultraviolet photometer for degenerate stars. Temperatures derived for hot helium-rich (DO)

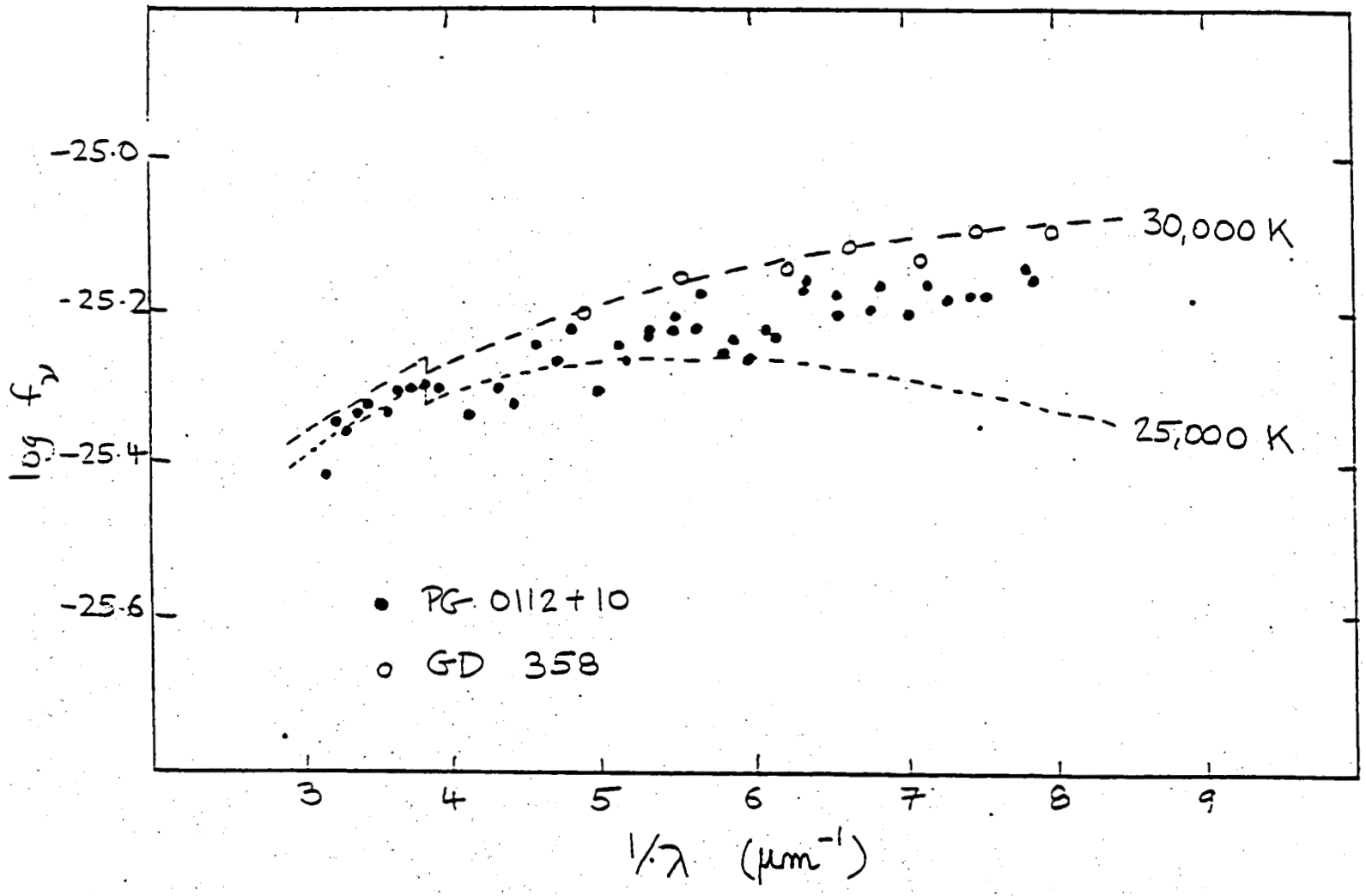
stars from IUE fluxes are sometimes substantially lower than those assigned from He II and He I (optical) absorption features. While questions remain about the accuracy of the IUE flux calibration, the problem arises in only some of the stars; the more likely culprit here is interstellar reddening. Standard ultraviolet extinction curves predicting as much 2200Å "bump" absorption as 1200Å absorption are simply unreliable, especially for these small amounts (Greenberg and Chlewicki 1983). Likewise, temperature assignments for hot DA stars can be made more reliably from hydrogen line strengths.

On the other hand, IUE is playing an important photometric role for hot DB stars in the 20,000 - 40,000 K range. This range represents the broad peak of He I opacity, and the line profiles show remarkably little variation. While it would seem that precise optical photometry (i.e., Stromgren, multichannel) should be accurate enough, there have been numerous instances of systematic errors due to differing photometric systems in use. IUE can therefore play a dominant role in establishing the temperature boundaries of the newly-discovered DB pulsational instability strip (i.e., Winget et al. 1982, 1984; Koester, Weidemann and Vauclair 1983). In Figure 1, I show a fit by Francois Wesemael to the first discovered pulsating DB star GD358, using pure helium, blanketed logg = 8 models from Wesemael (1981). We get a marginally higher temperature estimate (~ 28,000 K vs. 26,000 K) than Koester et al. Curiously, the other displayed DB star (PG0112+10) obviously has a very similar temperature but does not pulsate (Winget 1983, private communication)! Finally, the IUE fluxes severely constrain the temperature of the strange hybrid He, H composition object GD323 to be near those for pulsating DB stars (Liebert et al. 1984).

Ultraviolet spectra and energy distributions from IUE have resulted in drastically altered temperature estimates and composition interpretations for two magnetic white dwarfs. To be sure, the temperature determination for the low field (~ 1.8×10^7 gauss) star Feige 7 was consistent with prior optically-based values and implied a normal white dwarf radius (Greenstein and Oke 1982). However, these authors derived a substantially higher temperature (~ 14,500 K) for the high field magnetic degenerate star Grw+70°8247 by rigorously fitting the extended energy distribution. This would imply an abnormally small radius (~ 0.007 $R_\odot$) and correspondingly large mass. On the other hand, the ultraviolet energy distribution shows evidence for extensive blanketing, especially below 1400Å, which can affect this conclusion. Greenstein (1984) now attributes this blanketing to Ly α absorption, in agreement with Angel's (1979) composition hypothesis for this star. Finally, it should be noted that the IUE fluxes for another strongly-magnetic case, GD229, result in a drastic revision of that star's temperature -- but this time the direction is downwards (Green and Liebert 1981)!

WHITE DWARFS IN BINARY SYSTEMS

Ultraviolet spectroscopy is an invaluable tool for the study of binaries containing a hot white dwarf, both detached systems and cataclysmic variables (CVs). In many cases, IUE has provided the first direct study of a white dwarf component. Examples for detached systems include the DA companion of the G8 IIIp barium star Zeta Cap (Böhm-Vitense 1980), the DO companion to


-25.0
-25.2
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-25.6
log f_λ
30,000 K
25,000 K
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GD 358
3
4
5
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8
9
1/λ (μm⁻¹)

Figure 1.

HD149499 (Sion, Guinan and Wesemael 1982), and such short-period products of common envelope evolution as the Hyads V471 Tau and HZ9 (Guinan and Sion 1984).

It is often possible to make direct determinations of other stellar parameters besides the temperature. The cool companion's radial velocity provides the systemic reference from which the gravitational redshift and mass of the white dwarf may be estimated from echelle observations. Sion and Guinan (1983) find an implied mass of 0.5 $M_{\odot}$ for HD149499B, the first direct determination for a hot helium star. Moreover, the relative masses at least may be obtained from radial velocity curves for close pairs, generally the cool star is measured with a high-disperison optical spectrograph. Finally, line profile analyses permit gravity determinations by "atmospheric" techniques and comparison to isolated white dwarfs.

CATACLYSMIC VARIABLE PRIMARY STARS

Direct observations of the white dwarf in several CV systems have been possible, for the first time, using IUE. Such observations are both opportunistic and complicated to interpret. The accretion disk generally dominates the energy output at ultraviolet wavelengths. However, some dwarf novae and perhaps all of the diskless AM Herculis objects go into such low accretion states that the white dwarf primary dominates the ultraviolet energy distribution. Important examples include MV Lyrae (Robinson *et al.* 1981), VW Hyi (Mateo and Szkody 1984), and probably U Gem in quiescence (Panek and Holm 1983). All appear to have hot ($T_{eff} \geq 40{,}000$ K) components, though this may be due to selection. In the case of the recent low state of TT Ari (Shafter *et al.* 1984), the spectrum of the white dwarf at optical wavelengths permits a standard photospheric analysis. The star can be classified DAO, yields $T_{eff} \sim 70{,}000$ K, and a He/H ratio not too different from solar, as expected for recently-accreted matter. Moreover, the agreement between optical and IUE temperature determinations leaves no evidence for temperature variations across the surface of the accreting star. This is in contrast to the situation for the magnetic AM Her in its low state. Schmidt, Stockman and Margon (1981) suggested $T_{eff} \leq 22{,}000$ K from their analysis of the magnetic primary's optical spectrum, but Szkody *et al.* (1982) required $T_{eff} \sim 50{,}000$ K to fit the ultraviolet. The obvious answer is that a residual polar hot spot dominates the ultraviolet, while larger, cooler areas of the photosphere dominate the optical light (Liebert and Stockman 1983).

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